

Progress in measuring neutrino quasielastic interactions

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Abstract. This is an exciting time for folks who are looking at neutrino cross sections, and the especially important quasielastic interaction. We are able to inspect several recent results from K2K and MiniBooNE and are looking forward to a couple more high statistics measurements of neutrino and anti-neutrino interactions. There is additional interest because of the need for this cross section information for current and upcoming neutrino oscillation experiments. This paper is a brief review of our current understanding and some puzzles when we compare the recent results with past measurements. I articulate some of the short term challenges facing experimentalists, neutrino event generators, and theoretical work on the quasielastic interaction.

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INTRODUCTION

As this century's neutrino oscillation experiments have produced their first results, so have the associated neutrino interaction measurement efforts. The K2K[1, 2] and MiniBooNE[3] experiments have presented their investigations of the charged-current quasielastic (CCQE) neutrino cross section $\nu_\mu + n \rightarrow \mu^- + p$ in carbon and oxygen. MiniBooNE has additionally shown its first distributions for the anti-neutrino cross section. Their initial results seem to be at odds with the previous measurements from deuterium bubble chamber experiments.

Upcoming neutrino oscillation experiments depend heavily on the quasielastic interaction. It is a very large portion of the event rate around 1 GeV where oscillations are expected and where the current neutrino beams are tuned. Also, the two-body kinematics of this interaction are vital for obtaining an estimate of the incident neutrino energy spectrum for those experiments that depend on Cerenkov light, such as MiniBooNE and SuperK. An apparent puzzle with this cross section is a concern, whether it is due to cross section, nuclear, or experimental systematic effects.

STATUS OF EXPERIMENTAL RESULTS

There are two kinds of CCQE measurements. The direct measurement of a cross section is based on the measured rate divided by the flux and the number of targets, usually expressed as $\sigma_{QE}(E)$. It is a difficult measurement to make because we are challenged to improve our knowledge of the neutrino flux in our experiments. The alternative is an analysis of the shape of the Q^2 distribution which can be less dependent on the flux uncertainties. Such results assume the vector form factors are given by electron

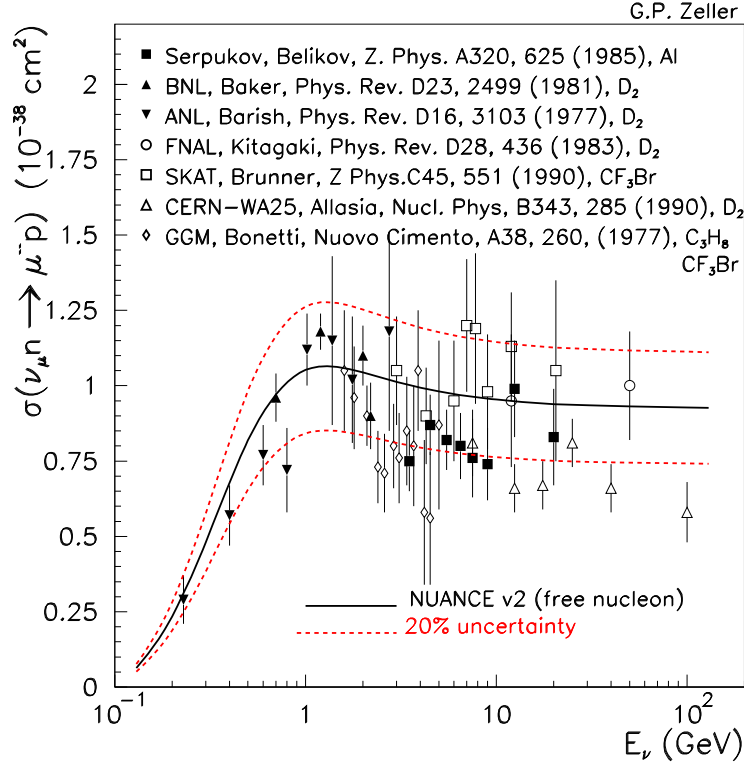


FIGURE 1. Summary of most of the pre-2000 data on neutrino CCQE interactions, plot courtesy of G. Zeller[5]. The data from BNL, ANL, and FNAL, are based significantly on a shape fit to the Q^2 distribution, the others use a determination based on their rate and flux, or a mix of rate and shape.

scattering experiments and extract information about the axial vector form factor, most often assuming a dipole shape with one free parameter, the axial vector mass M_A . Using the formalism summarized by Llewellyn-Smith[4] and the extracted form factors, we obtain information about the total cross section, though this is a somewhat more model dependent statement. The previous world measurements of the quasielastic cross section have been summarized in plots such as Fig. 1.

An important consideration in this plot is that it contains a mix of the two different techniques, and the bubble chamber measurements at the lowest energies (the BNL and ANL data) are from fits to the shape of the Q^2 distribution. These lowest energy measurements are also the measurements that had the smallest errors on the extracted value of M_A and dominated the global fits for M_A that were used in neutrino event generators until recently.

A sequence of papers that provide excellent lesson on this point are from the Argonne National Lab (ANL) experiment[6]; their publications contain results using four methods with different dependencies on the uncertainty in their neutrino flux. In that case, the estimated cross section comes out 20% lower (approximately one sigma); the errors are dominated by the uncertainty in the flux. The $\sigma(E)$ points used in the plot above are

based on an analysis that uses their flux-independent shape of the Q^2 to get an M_A , then re-extract a flux. This new flux is averaged with their default flux to produce those data points. Ideally, both techniques would produce compatible results. We still understand the ANL authors' conclusions: the tension between these two results can be understood to mean that the uncorrected flux estimate was too high or the shape of the Q^2 distribution and the axial form factors does not map so simply to the total $\sigma(E)$. One sigma is not a large discrepancy, but an oscillation experiment must assign an error and mitigate the effects of a large uncertainty on $\sigma(E)$, rather than the smaller errors on the shape of $d\sigma/dQ^2$.

The new results

I summarize the newest results very quickly, more detailed information is available elsewhere in these proceedings or in their publications. There are three new determinations of M_A from the shape of the Q^2 distribution, all of which are higher than the bubble chamber results. K2K reports a value of 1.20 ± 0.12 from the SciFi detector[1] using a mixture of water and aluminum as a target, and also a preliminary result of 1.14 ± 0.11 from the SciBar detector[2] using a scintillator (CH) target. These two experiments share some systematic errors in the beam flux and muon momentum determination, and have not yet given guidance about whether the results should be combined.

The MiniBooNE experiment has added a very high statistics measurement and also investigated a way of parameterizing the very low Q^2 region[3]. They obtain a value for $M_A = 1.23 \pm 0.20$ using this parameterization and 1.25 ± 0.12 when repeating their analysis with only M_A as a parameter and not including the very low Q^2 region in their fit, similar to the technique used by K2K and the bubble chamber experiments. That these results are higher is saying that there are relatively more events at high Q^2 compared to the default Monte Carlo simulation predictions.

The MiniBooNE result is noteworthy for several reasons. It is the first of what I will call an "enormous statistics" measurement, which will give them other avenues to understand systematic effects. For example they have shown their raw p_μ vs. θ_μ plot, in addition to the reconstructed Q^2 distribution. They also emphasize the essential need to understand the very low Q^2 region for their oscillation analysis; a description of this region had been neglected up to this point.

In the very near future, we expect to hear more information on quasielastic reactions from several sources. The NOMAD experiment expects to have a final QE result on a modestly short timescale. There is a little new information on the QE-like event rate in the emulsion in the CHORUS experiment[7]. The analysis of the MINOS data is currently underway; they are sitting on the next enormous statistics dataset. MiniBooNE has started showing distributions from anti-neutrino running, and is also expected to provide information using the rate/flux method. They state that their flux is constrained to 15% via the HARP hadron production measurements and other analyses.

On a somewhat longer timescale we expect results from SciBooNE, the SciBar detector operating in the MiniBooNE beam, which has already taken a significant amount of anti-neutrino data. After that will come yet another enormous statistics analysis from

the MINERvA experiment, including a systematic investigation of the QE reaction on different nuclear targets CH, He, C, Fe, and Pb. The MINERvA and MINOS measurements are on different nuclei and a different energy range than the K2K and MiniBooNE results. The MINOS experiment now has and the MINERvA experiment expects to have 800,000 quasielastic interactions with energies between 1 and 20 GeV, as predicted by their Monte Carlo and estimates of their run plan.

UPCOMING EXPERIMENTAL CHALLENGES

Systematic Errors

The reconstructed Q^2 distribution is affected by several systematic errors that are a challenge to control and which have overlapping effects on the analysis and final errors. If the primary focus of a shape fit is the Q^2 distribution, then the shape of the beam flux, the size of the bias in the muon momentum reconstruction, and the Q^2 shape as parameterized with M_A have interlocking correlations. I will ignore systematics related to event selection and resolution, which are too experiment specific to discuss here.

The left plot of Fig. 2 shows the distortion of the Q^2 spectrum produced by a muon momentum bias. For this mono-energetic 5.0 GeV sample of neutrino-carbon interactions, the points are reconstructed with a -2.0% p_μ bias, relative to the histogram. If this was the only significant error, the extracted M_A would be biased between 5% and 10%. The raw p_μ and Q^2 would show this discrepancy while the θ_μ would be well reproduced, because this bias shouldn't have any effect on the angle reconstruction.

This bias can be caused by the detector material assay, magnetic field errors, optical model, track vertex or end biases, which are specific to each experiment. There may also be some latent bias in the GEANT3 or GEANT4 muon dE/dx simulation, depending how the experiment calibrates their momentum reconstruction. Especially for the lower energy beams such as used by MiniBooNE, SciBooNE, and the K2K near detectors, errors in modeling the (beyond the) Fermi gas removal energy parameters or the Coulomb interaction of the outgoing charged lepton could play a small role equivalent to an apparent p_μ bias.

The situation would be simple, except that another source of error has similar effects. The beams we use are usually peaked at some value, and the location of that peak depends significantly on the primary beam targeting and the hadron focusing optics; an illustration of some uncertainties involved can be found in [8]. The right-side plot in Fig. 2 is a simplified demonstration of this; the mono-energetic beam is shifted low by 2% for the points. This plot shows the distortion of the $\cos \theta_\mu$ distribution. There is a trivial 2% distortion of the p_μ distribution as well, but the Q^2 distribution comes out undistorted. Note, this is actually a small bias in the shape of the underlying flux, relative to the width of the peak, typical E_ν binning, and resolution of these experiments.

Extracting M_A is now a challenge if the external constraints on the pair of systematic parameters are not very strong. If one or the other is not negligible, the analysis technique should attempt to incorporate both kinds of errors into the M_A fitting. The two published results [1, 3] have expressed different attempts to deal with this. The new and upcoming very large datasets may allow for more sophisticated ways of dividing up p_μ and θ_μ in

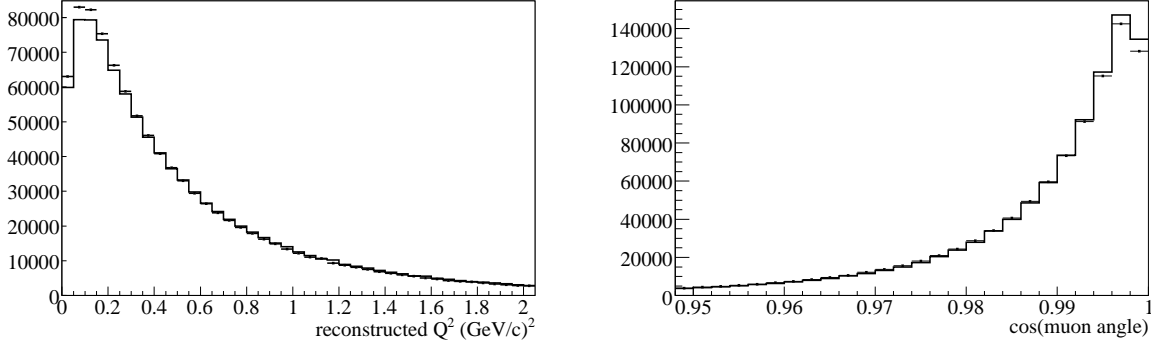


FIGURE 2. Two plots illustrating the effect of two systematic biases. Both are from a NEUGEN[9] calculation of ν_μ interactions on carbon. The nominal distribution is shown with the line. The points in the left plot of Q^2 have a -2% bias in p_μ , while the right plot of $\cos \theta_\mu$ has a -2% bias in E_ν . The statistical errors are negligible in both cases.

such a way that these systematics can be convincingly isolated with the neutrino data themselves.

Rate and Shape measurements

In my opinion, the other major task facing the experimentalists is to provide both rate and shape measurements of the quasielastic cross section. As discussed earlier in this paper, some experiments have done this in the past and reported slightly more than one-sigma discrepancies, when the large errors on the flux are taken into account. The BoONE and NuMI beams at Fermilab appear to offer the possibility of a flux constraint at least as good as was achieved in the past using the very large neutrino datasets and the existing beam instrumentation. Initiatives and upgrades to the NuMI instrumentation, driven by the MINOS and MINERvA experiments, may yield substantial improvement over this, and give better confirmation that the QE cross section model and M_A can adequately describe the Q^2 shape and the interaction rate at the same time.

UPCOMING THEORY CHALLENGES

Beyond Fermi gas and attention to reconstructed quantities

There is general concern that the implementation of nuclear effects in the current neutrino event generators is inadequate. These enormous statistics data sets are likely to reveal more deficiencies than in the past, and there are several efforts underway to incorporate better models. This includes spectral function and related models which take into account correlations between nuclei in the nuclear target, and also improved final state hadron rescattering models.

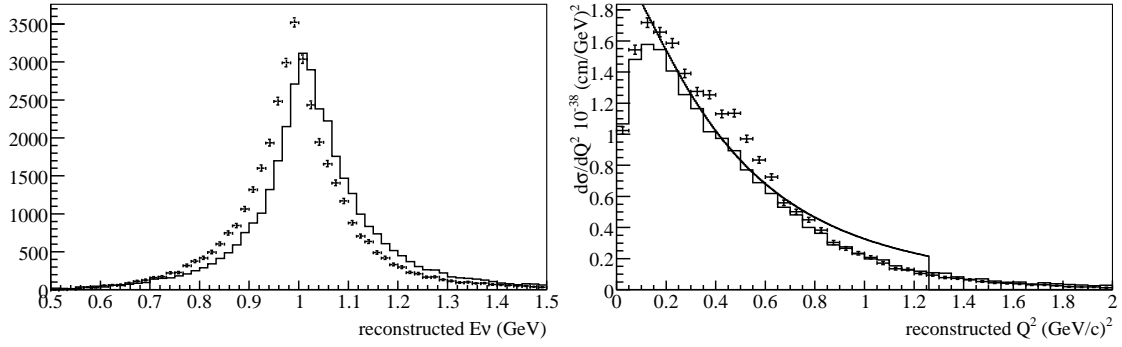


FIGURE 3. A comparison of the reconstructed Q^2 and E_ν quantities for the NEUGEN (solid histogram) and NEUT (points with statistical errors) event generators. The Q^2 plot has the distribution scaled to represent the effective cross section for a single one of the neutrons in oxygen, and the additional solid line shows the corresponding cross section for interactions with a single free neutron. The reasons for the visible distortions in these spectra are described in the text. The statistical errors for NEUGEN are similar to the ones shown for NEUT.

As these new calculations become available, it is important to take note of the definition of reconstructed Q^2 and E_ν being used to report the experimental results. There are additional distortions to these reconstructed spectra, above what would be expected from the techniques familiar from electron scattering. This definition starts with the usual expression

$$\text{reconstructed } Q^2 = 2E_\nu(E_\mu - p_\mu \cos \theta_\mu) - m_\mu^2.$$

A major difference from current theory calculations and experience from electron scattering is that the value of the neutrino energy E_ν is not known on an event by event basis. In this case, the neutrino energy can be estimated with the following expression

$$\text{reconstructed } E_\nu = \frac{(m_N + \varepsilon_B)E_\mu - (2m_N\varepsilon_B + \varepsilon_B^2 + m_\mu^2)/2}{m_N + \varepsilon_B - E_\mu + p_\mu \cos \theta_\mu}$$

where $\varepsilon_B \approx -27$ MeV for Oxygen is the removal energy and here I take it to be intrinsically negative. This expression is then used in the Q^2 calculation. This reconstructed E_ν is smeared and possibly biased because of the nucleon momentum distribution, even before considering detector resolution effects; a comparison of the smearing from NEUGEN[9] and NEUT[10] models is in the left hand plot of Fig. 3. This use of a reconstructed E_ν introduces one of several distortions into the reconstructed Q^2 spectrum, shown in the right hand plot of Fig. 3. A related expression can be used if the event likely produced a 1232 MeV resonance.

These plots show the reconstructed E_ν and Q^2 distributions for 1.0 GeV neutrinos incident on oxygen from the NEUGEN (solid histograms) and NEUT (points with statistical errors) neutrino event generators, with no detector effects or backgrounds. The right hand plot has been scaled to represent the cross section for a neutrino incident on just one of the eight neutrons in oxygen, though with no unfolding of the distortions. The solid line in the Q^2 plot is the free neutron cross section for a very similar set of model parameters as NEUGEN.

There are several causes for the visible distortions in that Q^2 spectrum. The choice of $M_A = 1.1$ GeV for NEUT increases the cross section by about 10%, compared to NEUGEN and the given free neutron line. Pauli blocking is implemented for both event generators, suppressing the very low $Q^2 < 0.2$ (GeV/c)² region. The kinematic cutoff just above $Q^2 = 1.25$ (GeV/c)² is smeared out by the neutron Fermi motion. These are relatively large effects.

But there are more interesting things in this comparison, which need to be addressed with more careful calculations of the nuclear environment. The NEUGEN code implements a tail to the Fermi motion distribution that goes up to 500 MeV/c based on the paper by Bodek and Ritchie[11]. Both event generators have a peak structure near $Q^2 = 0.5$ (GeV/c)² when using these reconstructed quantities, but this structure is smeared out for NEUGEN because of this tail and is not as prominent. Other aspects of a beyond-the-Fermi gas distribution would have different, potentially observable distortions of this reconstructed Q^2 spectrum that would not be apparent in a simpler Q^2 spectrum. A related question is what removal energy is appropriate for this reconstruction, when an experiment applies it to both data and Monte Carlo? The removal energy, off mass shell nature of the nucleon, and their effects on the resulting lepton kinematics should be inspected, and may contribute to shifts in the reconstructed E_ν spectrum and distortions of the reconstructed Q^2 spectrum.

In addition to this reconstruction Q^2 quantity, these new enormous statistics data samples may allow us to provide comparisons of the direct p_μ and θ_μ quantities and compare data and model in this parameter space. It may not be possible to explicitly provide the energy transfer ω at fixed angle as can be done for electron beams, but we should consider that there may be a way of more directly expressing the observed lepton kinematics. And of course, none of these distributions address uncertainties in the rescattering of the recoil proton.

Very low momentum transfer

Finally, I briefly mention the never understood very low $Q^2 < 0.2$ (GeV/c)² region. This has historically been an area of great model uncertainty, and a difficult one to address through electron scattering experiments. Difficulties in reproducing the data distributions may be related to an intrinsic problem with the Q^2 spectrum, or partially due to a distortion of the reconstructed Q^2 spectrum. This part of the spectrum corresponds to forward going muons in these experiments, where traditionally the detection efficiency is outstandingly high and uniform, but where the angular resolution of the detectors may play a role. Because it figures prominently in the MiniBooNE oscillation analysis, and because they have presented a parameterization to account for it, it has received renewed attention. The discussion in the coming years will likely lead to more suggestions for the cause of this, and ideas about how to extract information from the current and upcoming neutrino data.

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